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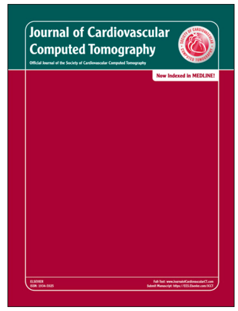

Transcatheter mitral valve replacement in mitral annulus calcification – “The art of computer simulation”

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Abstract

There is considerable interest in transcatheter prosthetic valve treatment for mitral valve disease in high-risk individuals. Although the presence of mitral annular calcium (MAC) may provide an anchoring zone for such devices, results to date have been modest with reported technical failure rates approaching 30% in specialist centres. This in part relates to the risk of left ventricular outflow tract obstruction and device dislodgment but also to the lack of specific imaging guidelines to plan for such procedures. We present the use of finite element analysis and computer simulation based on cardiac CT in three patients with severe MAC in whom transcatheter devices were considered. In the first two cases, the computer simulations were performed after the clinical procedure and were concordant with the clinical outcome. For the third case, computer simulation was performed prior to the clinical procedure. This indicated unsuitability for transcatheter device deployment and a subsequent medical management was adopted. Overall, our initial results suggest that computer simulation may have the potential to improve patient selection for transcatheter mitral valve replacement in the presence of significant MAC.

Transcatheter Mitral Valve Replacement in Mitral Annulus Calcification – "The Art of Computer Simulation"

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Conflicts of interest

None to declare.

Key words

Mitral annulus calcification; Transcatheter mitral valve replacement; Cardiac computed tomography; Computer simulation; Finite element simulation.

Introduction

In mitral valve annulus calcification (MAC), the fibrous integrity of the annulus becomes gradually replaced by calcium.[1] MAC may be associated with mitral valve stenosis (MS) or regurgitation (MR). Although in such instances conventional mitral valve replacement (MVR) surgery remains the first line treatment, the presence of MAC may require surgical debridement which can result in ventricular or atrioventricular groove rupture and damage to the adjacent coronary arteries.

Given these challenges, there has been considerable interest in the use of less invasive transcatheter therapies for mitral valve disease, using both self-expanding and balloon inflatable transcatheter aortic valves.[2-4] Although these have shown some early promise, complication rates remain high.[5] The principal aim of the current study was to determine whether computational modeling of transcatheter mitral valve replacement (TMVR) with aortic prostheses in patients with significant MAC has the potential to a improve patient selection and reduce complication rates.

Methods

Patients

In this study, 3 patients with MAC were considered for a TMVR procedure using aortic prostheses in the mitral position. All patients underwent retrospectively ECG-gated multiphase cardiac CT scans covering the entire cardiac cycle and computer simulations to predict the effects of device deployment within the mitral position with respect to conformity to the native mitral valve annulus and the likelihood of left ventricular outflow tract obstruction (LVOTO).

Cardiac CT scans

All cardiac CT scans were performed using a 256-slice multi-detector row CT scanner (Brilliance iCT, Philips Healthcare, Best, The Netherlands). A total of 100 ml of intravenous contrast (Omnipaque, GE Healthcare, Princeton, NJ, USA) was injected (5 mL/s) via a power injector into the antecubital vein. Retrospectively ECG-gated spiral scanning was performed with a single breath-hold technique and a delay of 10-12 seconds after contrast detection in the ascending aorta. Data acquisition parameters included a heart rate-dependent pitch of 0.2-0.45, a gantry rotation time of 270 ms, a tube voltage of 100 or 120 kVp depending on the patient's body mass index and a tube current of 125-300 mA, depending upon the thoracic circumference.

Computational modeling

From the CT scans, three-dimensional computer models of the left heart were created using image dedicated segmentation techniques (Mimics software v18.0, Materialise, Leuven, Belgium) by FEops (Gent, Belgium). The output of this segmentation process was subsequently used to generate a finite element mesh of the complete mitral valve apparatus, including the calcified mitral valve annulus, the (calcified) leaflets and the chordae. Three types of chordae were modeled: marginal chords that connect to the free edge of the leaflets, strut chords inserting at the body of the anterior leaflet, and basal chords inserting at the body of the posterior leaflet. Varying mechanical properties were automatically assigned to different tissue regions. Following this, detailed computer models of the valve that accurately represented mechanical device behavior (e.g. braided wires, locking mechanism) were virtually implanted in the patient-specific left heart models using finite element simulations. All simulations were performed using the Abaqus/Explicit v6.14 finite element solver (Dassault Systèmes, Paris, France). In each computer-simulated implantation, all steps of the clinical or in-vivo implantation (if performed) were respected consisting of valve size selection, and implantation position (Figs. 1-3, Movie clip 1). The simulation run-time was <3 hours using an Intel Core i7-6900K (3.2 GHz) processor. Since this was an exploratory study, for cases 1 and 2 the computer simulations were undertaken after the clinical procedure had been performed. For case 3, the computer simulation was performed prior to any clinical procedure and was used to determine anatomical suitability.

Results

Case 1

A 65-year-old patient with the history of prior TAVR presented with increasing shortness of breath. The transthoracic echocardiogram (TTE) showed severe MR with a left ventricular ejection fraction of 65%. Subsequent cardiac CT revealed extensive MAC with dystrophic involvement of basal myocardial segment (Figure 1). The patient was considered to be too high-risk for surgical MVR (Society of Thoracic Surgeons [STS] risk score 18%). Following standard geometric sizing and planning with transesophageal echocardiography (TEE) and cardiac CT, a Lotus valve (Boston Scientific, Marlborough, MA, USA) was implanted in the mitral position. The procedure was uneventful and at 6-month follow-up there was no residual MR, device dislodgment or LVOTO. In this case, the computer simulation performed after the procedure was concordant with the pre-implantation CT evaluation in predicting suitability for TMVR.

Case 2

A 69-year-old man with a background history of atrial fibrillation, prior coronary artery bypass grafting and TAVR presented with increasing shortness of breath. TEE demonstrated heavy calcification and restriction of the mitral leaflets giving rise to significant MS. Cardiac CT demonstrated the presence of circumferential MAC (Figure 2). The patient was considered to be at too high risk for surgical MVR (STS risk score 17%). Following cardiac CT planning, the patient underwent implantation of a Lotus valve in the mitral position under direct TEE guidance. He subsequently developed acute pulmonary oedema secondary to malposition of the valve relative to the annulus which gave rise to severe paravalvular regurgitation. The valve was surgically explanted with further implantation of a Sapien 3 (Edwards Lifesciences Inc., Irvine, CA, USA) valve into a 34-mm memo 3D ring (MEMO 3D Sorin Group, Saliggia, Italy). In this case, the computer simulation performed after the procedure demonstrated unsuitability for TMVR owing to non-conformity of the prosthetic valve to the mitral valve annulus, potential device instability and a high risk of significant paravalvular regurgitation (Figure 2, Video 1). This was concordant with the unfavorable clinical outcome experienced.

Case 3

An 87-year-old woman with a history of atrial fibrillation and chronic kidney disease presented with increasing dyspnea. A TTE demonstrated extensive MAC with severe MR and preserved systolic function. She was considered to be at high surgical risk for MVR (STS risk score 23%). She subsequently underwent a cardiac CT scan which confirmed the presence of circumferential MAC, a small left ventricular cavity size and a basal septal bulge (Figure 3). This led to concerns relating to LVOTO with a TMVR with an aortic prosthesis. As a consequence, the cardiac CT scan was used for computer simulation to determine anatomical suitability prior to any device deployment. This confirmed that implantation of a transcatheter valve would result in a good seal with the annulus but irrespective of positioning (high, medium or low within the left atrium), significant LVOTO was likely to ensue. TMVR deployment of an aortic prosthesis in the mitral position was aborted. In this case, pre-implantation computer simulation was consistent with the standard geometric evaluation in predicting unsuitability for a TMVR.

Discussion

The main findings of the current study are that novel computational modeling techniques may be of value when applied to cardiac CT to aid patient selection and predicting patient outcomes following TMVR with aortic prostheses in patients with severe MAC.

In patients with severe mitral valve disease, the presence of significant MAC requires specific surgical techniques to repair or replace the abnormal mitral valve. Despite this, reoperation and mortality rates remain high.[6] Accordingly there has been considerable interest in the use of transcatheter therapies as an alternative to surgery. In the recently published Global Registry of TMVR with aortic prosthesis in patients with significant MAC, Guerrero et al reported the results of 64 patients from 32 centers who underwent transcatheter valve implantation in the presence of significant MAC. Of these, 59.4% underwent implantation of a Sapien XT valve (Edwards Lifesciences Inc., Irvine, CA, USA), 28.1% of a Sapien 3 valve (Edwards Lifesciences Inc., Irvine, CA, USA), 7.8% of a Sapien valve (Edwards Lifesciences Inc., Irvine, CA, USA), and 4.7% of an Inovare valve (Braile Biomedical, São José do Rio Preto, Brazil). Although there was an improvement in New York Heart Association functional class in 84% of patients, the reported 30-day all-cause mortality was 29.7%.[5] Despite the procedures being conducted at specialized centers, there was a technical failure rate in 28% of patients. A second device implantation was required in 17.2%, LVOTO occurred in 9.3% of patients whilst there was device embolization in 6.3% and cardiac perforation in 3% of patients.[5] Experience continues to gather and successful deployment of both Lotus valves and Direct Flow valves (Direct Flow Medical, Santa Rosa, CA, USA) in the mitral valve position has also been achieved.[2, 3] Ongoing studies such as the MITRAL trial (NCT02370511) which is designed to evaluate the safety and efficacy of Sapien XT (Edwards Lifesciences Inc., Irvine, CA, USA) or Sapien 3 implantation in 90 inoperable patients with MAC or with failed prosthetic valves will continue to inform the scientific community as to the merits of this approach.

Irrespective of the TMVR device or the clinical indication it is clear that careful pre-procedural imaging is vital. Detailed echocardiographic evaluation of the mitral valve is required along with ECG-gated contrast enhanced multiphase cardiac CT. Currently, the evaluation of CT datasets relies heavily on standard geometric measurements made by experienced practitioners of CT at specialized centers. With complication rates being high, there is good reason to suggest that this strategy may be imperfect in predicting the risk of LVOTO and significant paravalvular regurgitation regarding device migration following deployment.[7] From our experience, it is likely that these relate to: 1) an inability to predict how replacement transcatheter valves will conform to the mitral valve annulus in the presence of significant calcification, 2) how the calcification will behave under conditions of radial stress and 3) how the depth of implantation and aorto-mitral-annulus angulation influences the development of significant LVOTO.[8]

As computational modeling gains more prominence in cardiac imaging, there is hope that some of these techniques may refine conventional methods for interpreting cardiac CT datasets and provide added value for patient care. The current report indicates one potential area where computational modeling for a novel therapy may be of clinical use in improving patient selection and patient outcomes.

Conclusions

The current report suggests that the application of computational modeling to cardiac CT datasets may have the potential to enhance standard evaluation techniques for complex mitral valve interventions. Further work is indicated to evaluate these techniques in a prospective manner and in larger patient cohorts.

Acknowledgments

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Figure legends

Figure 1

Case 1: Pre-procedural CT and post-procedural computer simulations

Panel A shows the short axis view of the mitral valve, the conventional CT sizing measurements and the degree of mitral valve calcification. Panel B shows the apical long axis view and the relationship of the mitral valve annulus to the left ventricular outflow tract. The white line indicates the TAVR in situ and the white arrow the mitral valve annulus calcification. Panels C and D show the simulated transcatheter valve in situ from the left atrium and left ventricular perspectives. Panels E shows the predicted appearance of the left ventricular outflow tract following deployment and Panel F the three chamber view of the valve in the annulus to achieve the LVOT appearance in Panel E.

Ao: aorta, CT: computed tomography, LA: lefit atrium, LV: left ventricle, LVOT: Left ventricle outflow tract, TAVR: trans catheter aortic valve.

Figure 2

Case 2: Pre-procedural CT and post-procedural computer simulations

Panel A shows the short axis view of the mitral valve, the conventional CT sizing measurements and the degree of mitral valve calcification. Panel B shows the apical long axis view and the relationship of the mitral valve annulus to the left ventricular outflow tract. The white arrow shows the mitral valve annulus calcification. Panels C and D show the simulated transcatheter valve in situ from the left atrium and left ventricular perspectives. Note was made of a large area of malapposition between the valve and the annulus as potential substrate for significant paravalvular regurgitation. Panels E shows the predicted appearance of the left ventricular outflow tract following deployment and Panel F the three chamber view of the valve in the annulus to achieve the LVOT appearance in Panel E.

Ao: aorta, CT: computed tomography, LA: lefit atrium, LV: left ventricle, LVOT: Left ventricle outflow tract.

Figure 3

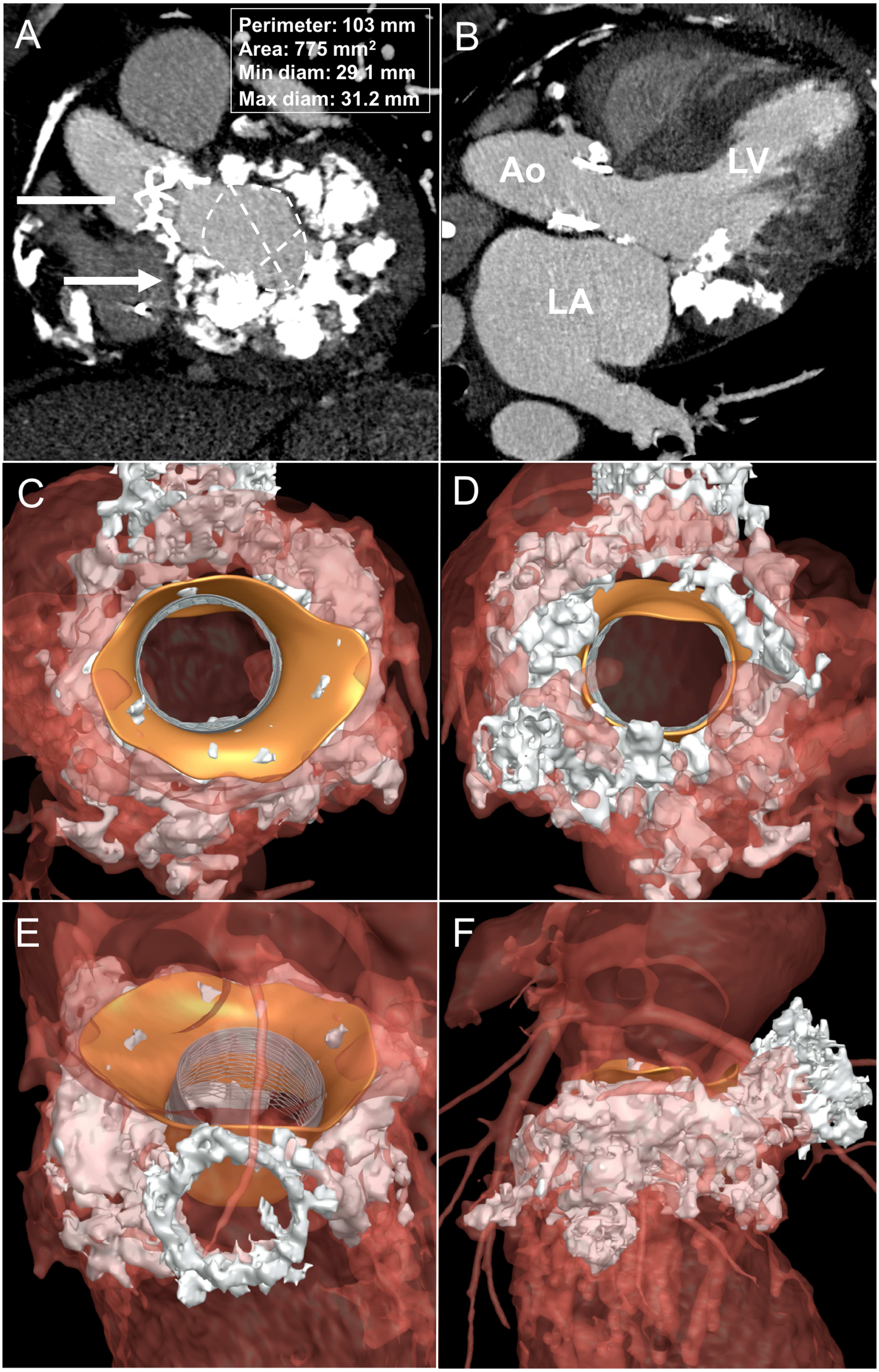
Case 3: Pre-procedural CT and computer simulations

Panel A shows the short axis view of the mitral valve, the conventional CT sizing measurements and the degree of mitral valve calcification. Panel B shows the apical long axis view and the relationship of the mitral valve annulus to the left ventricular outflow tract. The white arrow shows the mitral valve annulus calcification. Panels C and D show the simulated transcatheter valve in situ from the left atrium and left ventricular perspectives. Panels E shows the predicted appearance of the left ventricular outflow tract following deployment and Panel F the three chamber view of the valve in the annulus to achieve the LVOT appearance in Panel E.

Ao: aorta, CT: computed tomography, LA: lefit atrium, LV: left ventricle, LVOT: Left ventricle outflow tract.

Video 1

The computer simulation video shows malapposition of the prosthetic valve against the mitral valve annulus with potential for device dislodgment and paravalvular regurgitation.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LV
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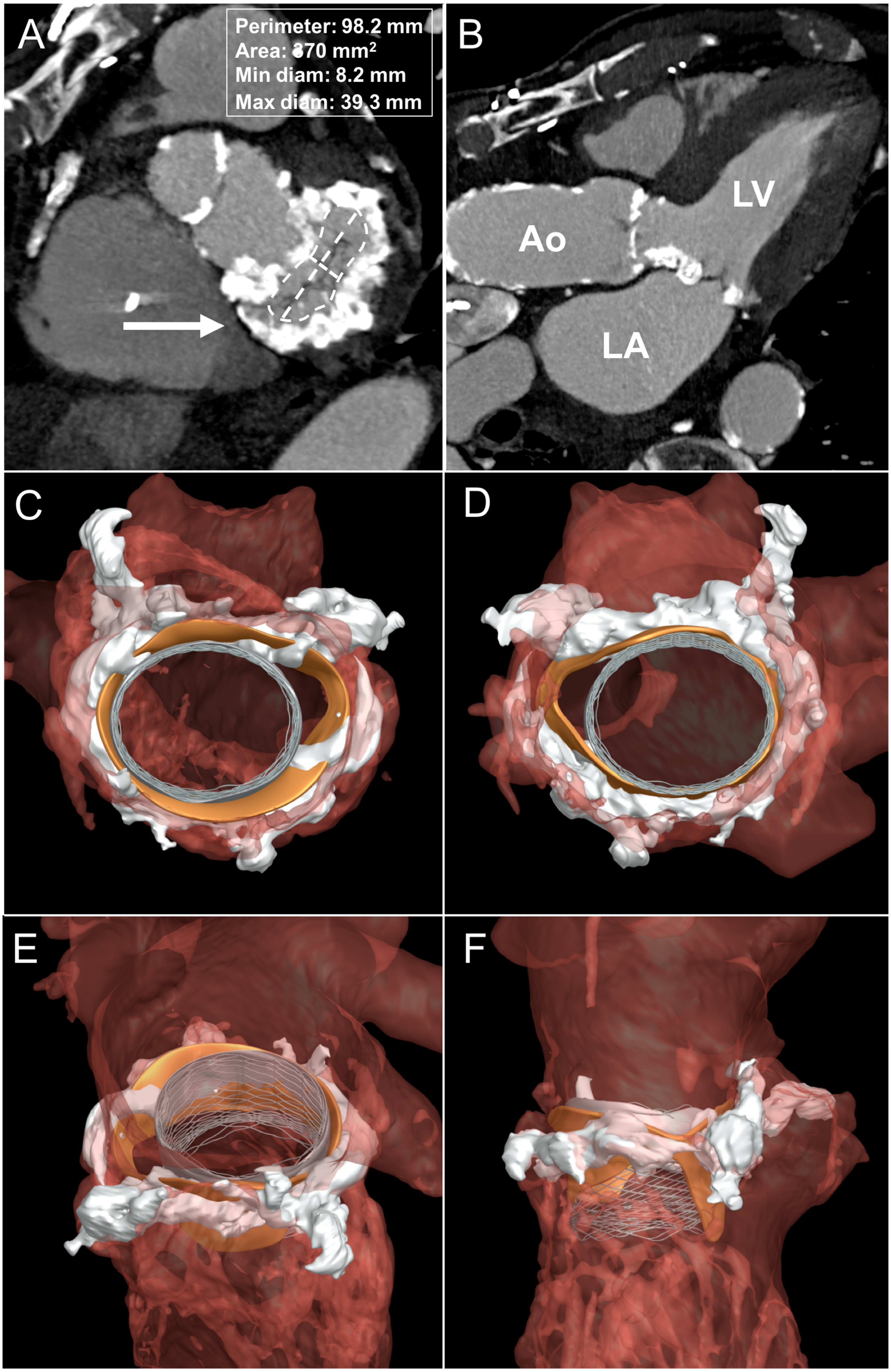
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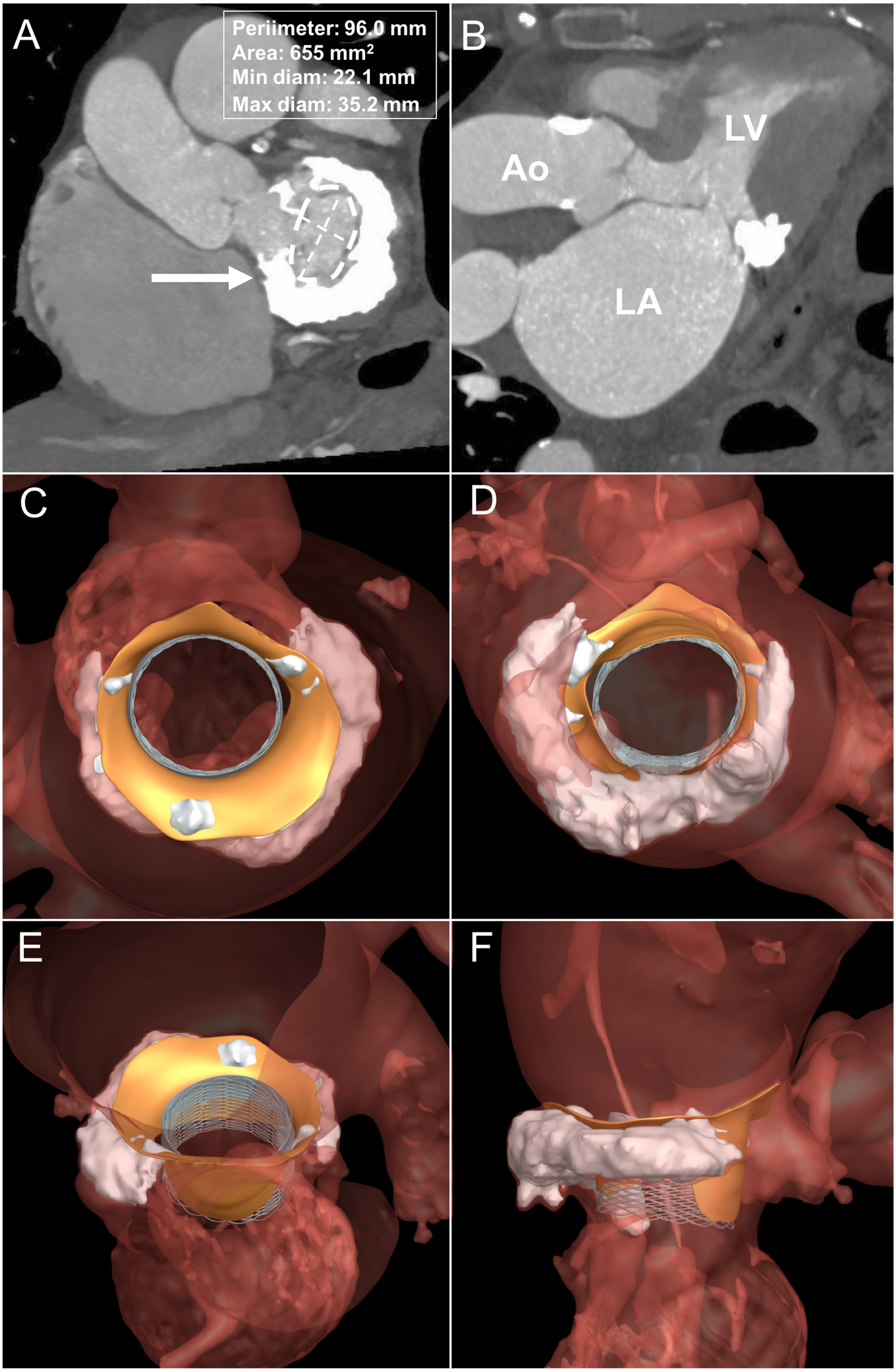
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